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Damage detection of laminated CFRP structures using electric pulse wave transmission

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Abstract.
Carbon Fiber Reinforced Polymer (CFRP) laminates are applied to many aerospace structures. For these laminated CFRP structures, it is quite difficult to detect internal damage such as delamination, matrix cracks, and local fiber breakages. Carbon fibers are adopted as reinforcement in CFRP and it is an excellent electric conductor at the same time. The carbon fiber has been used as a strain sensor for decades. Electrical resistance change measurement has advantages over other methods of structural health monitoring. The electrical resistance change method, however, requires a lot of electrodes on the target CFRP structures to measure electrical resistance change at multiple segments of the CFRP structure. The present approach adopts a pulse electric wave that transmits in a CFRP plate structure. CFRP has high conductivity in the fiber direction and the very low conductivity in the transverse direction. A pulse wave transmits in the carbon fiber to the end of the fiber. When fiber damages occur, the pulse wave is reflected by the damage. By the reflected pulse wave, we can detect the damages in the CFRP structures. A parallel plate cathode and a directional coupler were used here. The proposed new method was adopted for the unidirectional CFRP in the present study. Several modifications to obtain high performance of the reflected pulse wave were performed here. As a result, the method was experimentally proved to be effective for detections of carbon fiber damages.

Key words: CFRP, Composites, Electric Resistance, Fiber breakages, Pulse wave, Reflection

Introduction

Laminated Carbon Fiber Reinforced Polymer (CFRP) has been increasingly applied to the aerospace primary structures because of its high specific strength and stiffness. The CFRP laminate, however, delaminates easily by a slight impact load. That delamination crack reduces the compression strength and compression stiffness of the CFRP laminate. The delamination crack is, however, difficult to detect by a visual inspection. This causes the requirement of a monitoring method to maintain structural reliability and to reduce huge maintenance cost.

The CFRP laminate is composed of electrical conductive carbon fibers and insulating resin. Several structural health-monitoring methods utilize the electrical changes caused by applied load, temperature change, and fiber breakages have been studied [1-6]. Authors have proposed electrical resistance change method (ERCM) and electric potential change method to identify a delamination in the CFRP laminate [7-12]. In the ERCM, the delamination was estimated from the measured electrical resistances or electrical potential changes caused by a delamination using couples of electrodes mounted on the laminated CFRP plate surface.

For the ERCM, estimation performance is high although a lot of electric charges are required to measure electric resistances between all adjacent electrodes. Although the electric potential change method (EPCM) does not have high accuracy, the EPCM may enable to reduce the number of experiments. To improve the accuracy of the EPCM, a two-stage electric potential method (TS-EPCM) was proposed [11] [12] by authors. For the TS-EPCM, current electrodes and voltage electrodes are mounted separately to adopt a four-probe method. Only two charges of electric current are enough to monitor the delamination by measuring electric potentials at the voltage electrodes simultaneously.

The present study proposes a low cost method for a delamination monitoring of CFRP structures by means of measurements of the electrical resistance change with the help of an optimization method using FEM analyses. As a first step, a low cost method that requires only several experiments is proposed here. From the several experiments, electrical conductivity of CFRP is obtained using optimization method. Electrical conductivities of CFRP laminates in all direction are obtained by means of an optimization method from the electrical voltages at the multiple points of the CFRP laminate. Delamination cracks usually have crack surface contacts. This contact is very difficult to deal with. In the present research, the effect is approximated using equivalent conductivity in the thickness direction. The equivalent conductivity is obtained using the optimization method to fit the electrical voltage in FEM analyses with the measured experimental results.

The present approach adopts a pulse electric wave that transmits in a CFRP structure. The carbon fibers conducts electric current and the polymer resin can be treated as insulator. CFRP has high conductivity in the fiber direction and the very low conductivity in the transverse direction. The pulse wave transmits in the carbon fiber to the end of the fiber. When carbon fiber damage occurs, the damage reflects the electric pulse wave. Measurements of the reflected pulse wave, we can detect the carbon fiber damage.

The proposed new method utilizes the electrical resistance change of the carbon fiber bundle using the pulse wave, and the new method detects the location of the damaged area from the reflected time information. Since the new method uses transmitted wave in the target CFRP, the new method does not require a lot of electrodes. As a first step of the new method, basic researches using electric pulse waves are performed and a fiber breakage test and an indentation test are conducted to investigate the applicability of the new method using a unidirectional CFRP plate. Fiber damages are modeled as a mechanical notch and detectability of the small notches are experimentally investigated here.

Time domain reflectometry

Unidirectional CFRP has high electric conductivity in the fiber direction. In the transverse direction, however, the CFRP has low electric conductivity. The high electric conductivity enables us to use the carbon fibers as a computer network cable when the cable length is not long. In the computer network cable, such as Ethernet cables, electric conductive metallic wires are included and electro magnetic shielding with protective jacket covers the wires. Since the error of the electric pulse wave is significant for the computer network, a network analyzer has been developed. Using a pulse wave generator and a digital oscilloscope, reflected wave or transmitted wave of the cable can be analyzed and the location of the disconnection of the wire can be detected as shown in Figure 1.

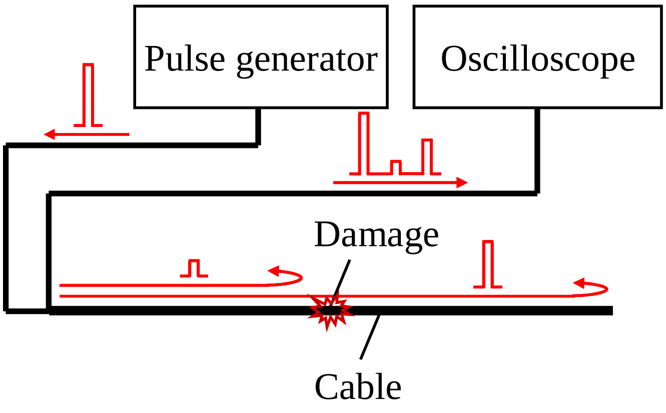


Fig.1 Schematic representation of TDR method

The distance to the damage from the electrode can be calculated using the equation as shown here.

$$L = \frac{V_p \Delta T}{2} \tag{1}$$

where L is the distance, ΔT is the time difference between the input pulse and the reflected pulse, and Vp is transmitted velocity in CFRP.

This technique is directly applied to the target CFRP structure if an electric pulse wave can be input in the target CFRP laminate. In the unidirectional CFRP, the pulse wave propagates in the fiber direction. If the pulse wave is applied to a bundle of carbon fibers, carbon fiber breakages in the part of the bundle may reflect the pulse wave and the reflected wave can be detected using the digital oscilloscope. Time difference of the transmitted wave enables us to know the location of the damaged part.

The new method requires reliable and low contact resistance electrodes. Otherwise, the electrodes reflect all part of the pulse wave. In order to make the reliable electrodes, electrical copper plating method is applied here. Figure 2 shows the electrical copper plating method used in the present research. In the previous study of the electrical resistance change method, the copper plating electrodes are confirmed to be very low contact resistance and it does not depend on the skill. Although it is tiresome work to make a lot of electrodes using the copper plating method on the CFRP, the new method hopefully requires only a few numbers of electrodes on the edge of the CFRP plate..

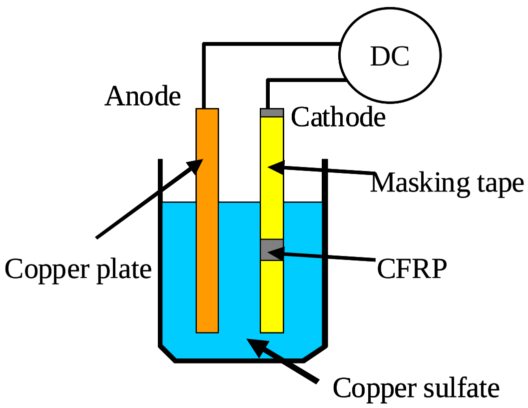


Fig.2 Electric copper plating method to make electrodes

Experiments

Material. CFRP laminates are fabricated from unidirectional prepreg sheets PYLOFIL#380 (Mitsubishi Rayon Co., Ltd). The fibers used are TR30S 12 l (tensile strength 4410 MPa, tensile modulus 235 GPa); the epoxy resin is a product designed for general use. Curing conditions are 130×°C× 90 min under vacuum pressure. Since the specimen length is too long for the small autoclave, film heater of 1m length is used to make specimens. The CFRP is unidirectional of stacking sequence of $[0_4]_T$. Specimens (1980mm long and 120mm wide) are directly cured from the CFRP prepreg. Thickness of the specimen is approximately 0.92 mm (Fig.3). Fiber volume fraction is approximately 60%. First half of the specimen is not cured but used as prepreg. Rest of the half of the specimen is cured at the curing temperature. This is because to make is easy to mount electrodes on the edge of the specimen using copper plating method. Figure 4 shows the electrode made at the end of the prepreg.Before the experimental tests, we checked that there was no significant difference in the electric pulse wave velocity between in the prepreg and in the cured CFRP.

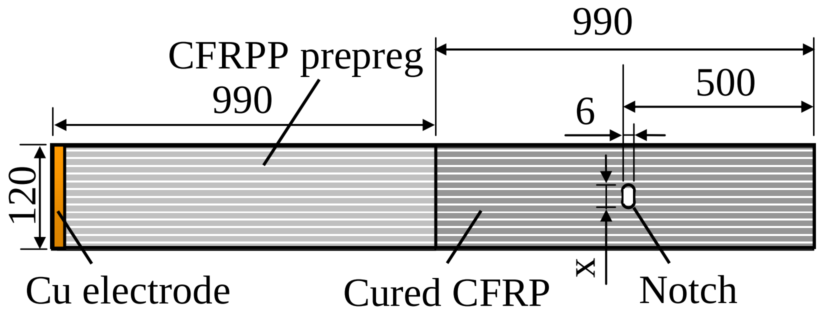


Fig.3 Specimen configuration

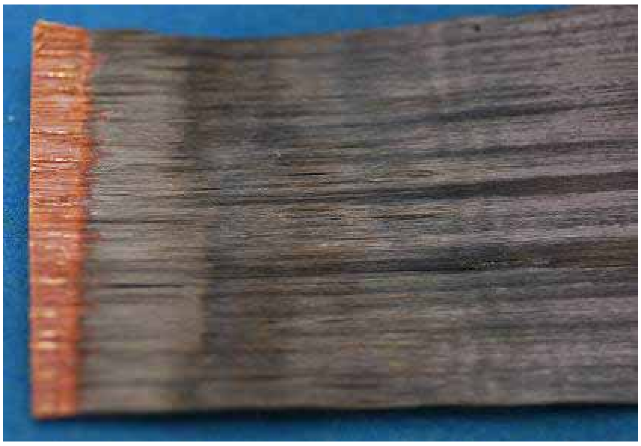


Fig.4 Electrode made by electric copper plating

Measurement of reflected pulse wave. A function generator of Tektronix AFG3251 is used as a pulse generator and Tektronix TDS5034 digital oscilloscope is used as a data storage machine for reflected pulse waves. These are connected as shown in Fig. 5. A directional coupler is used to remove the pulse wave from the generator here. To input the electric pulse wave, impedance matching between the initial cables and the target CFRP plate is indispensable. Since the electromagnetic properties of CFRP is not well known, aluminum plate is used to calibrate the impedance of the parallel plate electrical wave guide.

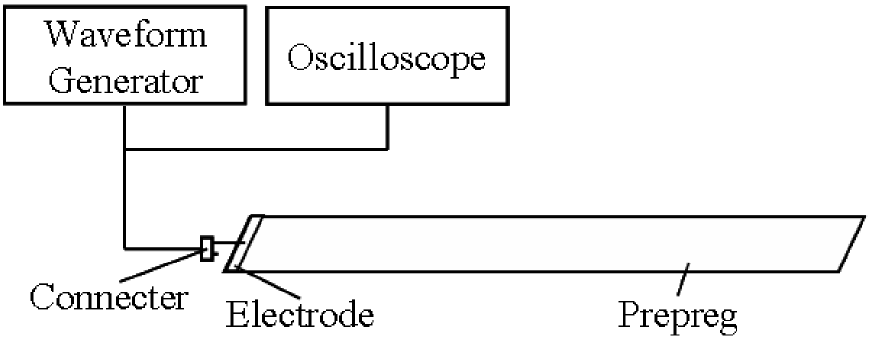


Fig.5 Experimental setup

Results and discussion

Basic modifications using specimens without notch. First of all, length of unidirectional CFRP specimens were measured by using the reflected pulse waves without parallel cathode plate. The lengths of the specimens are 1, 2 and 4 [m]. For calculations of the pulse wave velocity of CFRP, the relative permittivity (1.0006) and the relative magnetic permeability (1.0000) of air are used. Figure 6 shows the measured results. The abscissa is the time and the ordinate is the electric voltage. The green curve is the results of CFRP of 1 [m] length: the blue curve is the results of CFRP of 2 [m] and the red curve is the results of CFRP of 4 [m]. Although the reflected pulse is observed in each result, it is quite difficult to distinguish the time difference because the reflected pulse is very small.

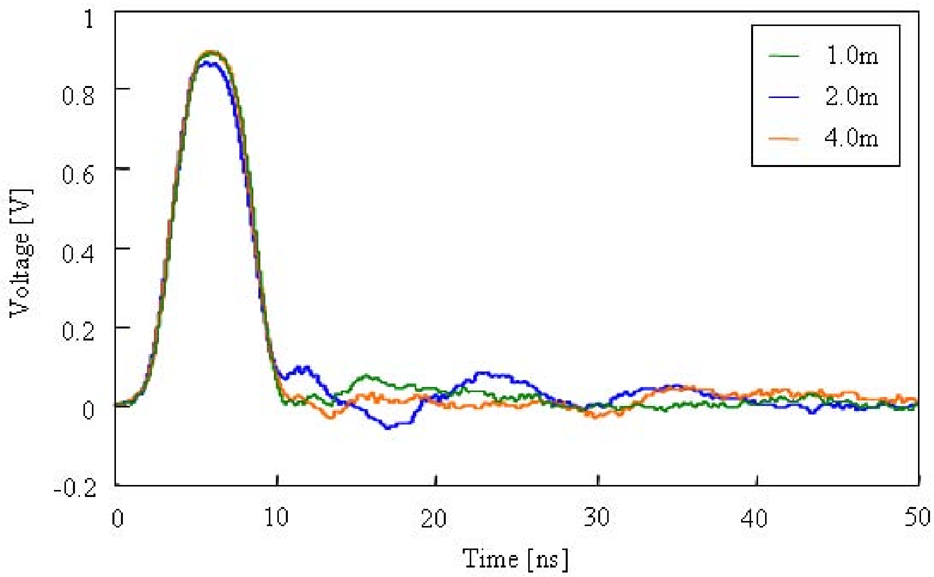


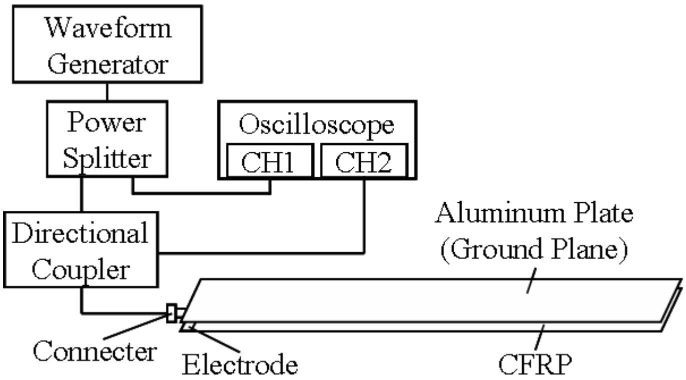
Fig.6 Reflected pulse wave measurements of various specimens of various lengths

Table 1 Calculated length of CFRP plate

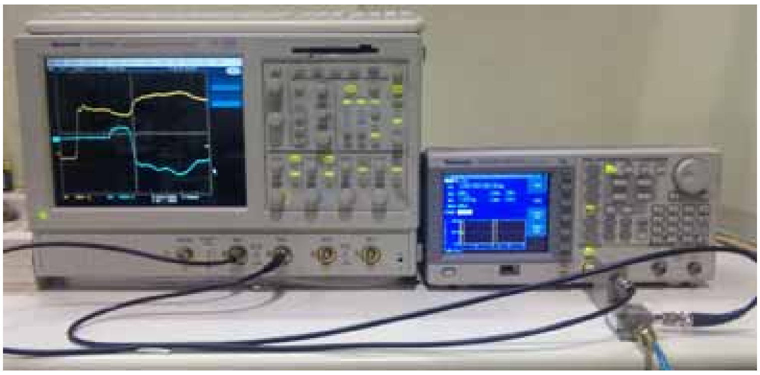
length [m]	Time[ns]	measured value[m]
1	7.4	1.11
2	14.6	2.19
4	28.0	4.20

Table 1shows the results of calculated length from the reflected wave although it is quite difficult to distinguish the reflected wave from the measured results. In the calculations, electromagnetic properties of air are used. Table 1 shows the calculated results almost agree with the actual length of the CFRP. This means that the Time Domain Reflectometry (TDR) method is applicable for CFRP plates.

In order to obtain clear reflected wave, impedance modification was performed with an aluminum plate. Without the aluminum plate, infinite grand is used as a real grand of the wave, and that means the electromagnetic wave is emitted to the air. This makes low reflection. To improve this low reflection, an aluminum plate of 5 [mm] thickness is used as a grand. Figure 7 shows the schematic representation of the modification to improve the reflected wave. In addition to the aluminum plate, a directional coupler and a power splitter are used to obtain reflected wave clearly.



(a) Schematic representation of modified system



(b) Oscilloscope and function generator

(c) Power splitter and directional coupler

Fig.7 schematic representation of modified TDR

This aluminum plate is not required when an adequate impedance matching circuit is available and electromagnetic noise is perfectly cut in this measurement system. Of course, we can use copper mesh layer, which is applied as an lighting protection system, as a ground in an actual aircraft wing, or we can use other CFRP layer as a ground.

To check the performance of this modification, a CFRP plate of 980mm length and 120mm width of $[0_4]_T$ is prepared. The plate is connected to the TDR system as shown in Fig.7. Three types of spacing between the aluminum plate and the CFRP plate are tested experimentally. The results obtained are shown in Fig.8. Except for the 1000 mm, clear reflected wave is observed with the aluminum plate. As shown in Fig.8, the results of spacing of 10 mm and 20 mm have high reflected wave. The results of 10 mm have higher reflected wave in the entire region compared with the results of 20 mm. In the present study, therefore, 10 mm spacing is adopted for the experiments.

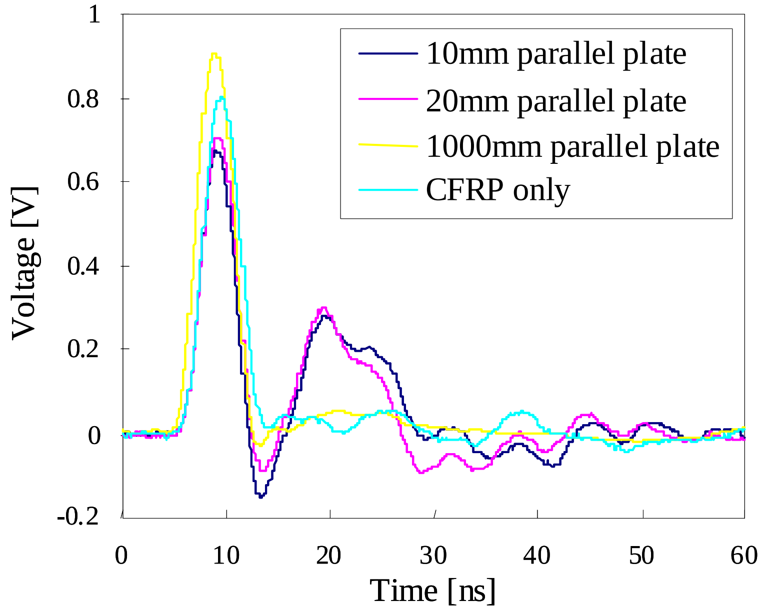


Fig.8 Measured results after modifications

Detection of fiber breakages using TDR. Using the modified system, the TDR is applied to the new specimen of 2 [m] length: the stacking sequence is the $[0_4]_T$. A notch was made using a drill of diameter of 6 mm. Seven types of notch length were made using the drill, and the reflected waves were measured. Figure 9 shows the results of the CFRP specimen of 2 m length.

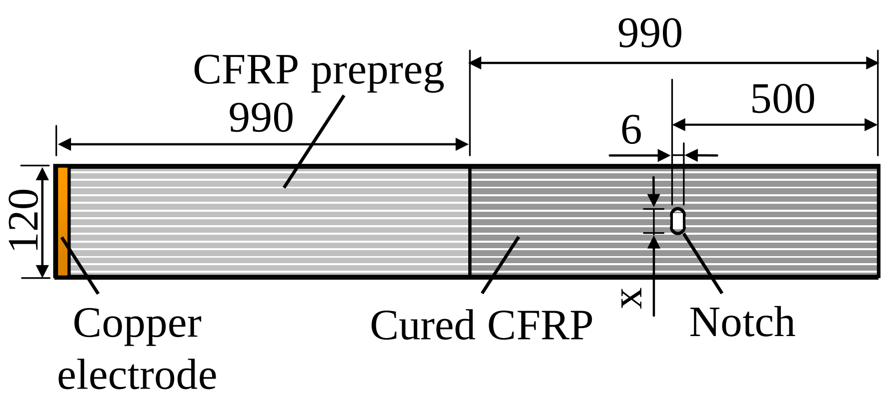


Fig.9 Specimen configuration used for the damage detection tests

In the notch detection test, the notch length types used here are 6, 18, 30, 42, 54, 66, 78 and 120 (fully [mm]. The notch was made at the quarter part of the CFRP from the right end of the CFRP plate. The results obtained are shown in Fig.10.

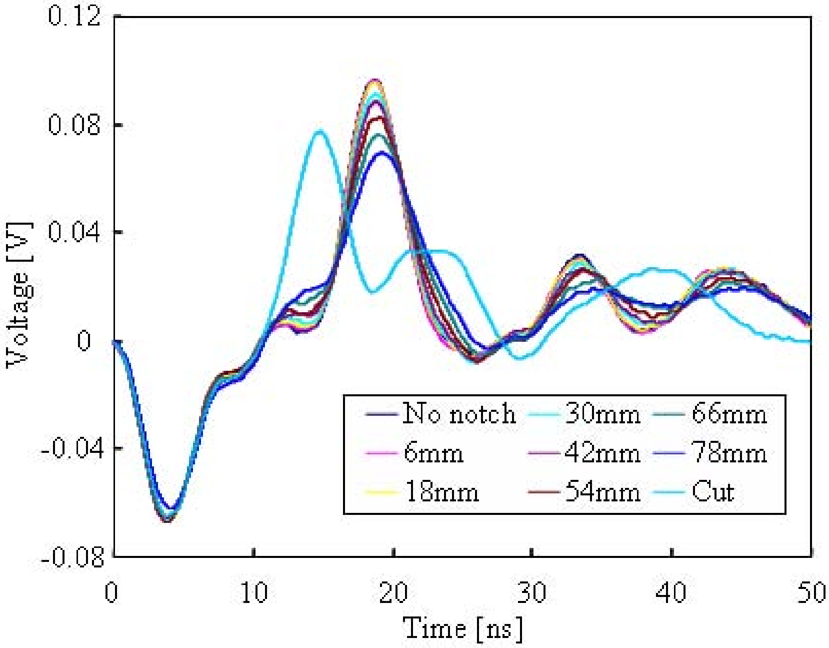


Fig.10 Results of notch detection

The solid right blue curve represents the result of perfectly cut at the notch line. The result shows the reflected wave exist at approximately 12 [ns] time. Other results show that the small reflected wave at the 12 [ns] time. Figure 11 shows the magnified view at approximately 12 [ns]. Figure 11 shows that the larger reflected wave exits with the increase of the notch length. At least, more than 30 [mm] length, the notch can be detected from the reflected wave.

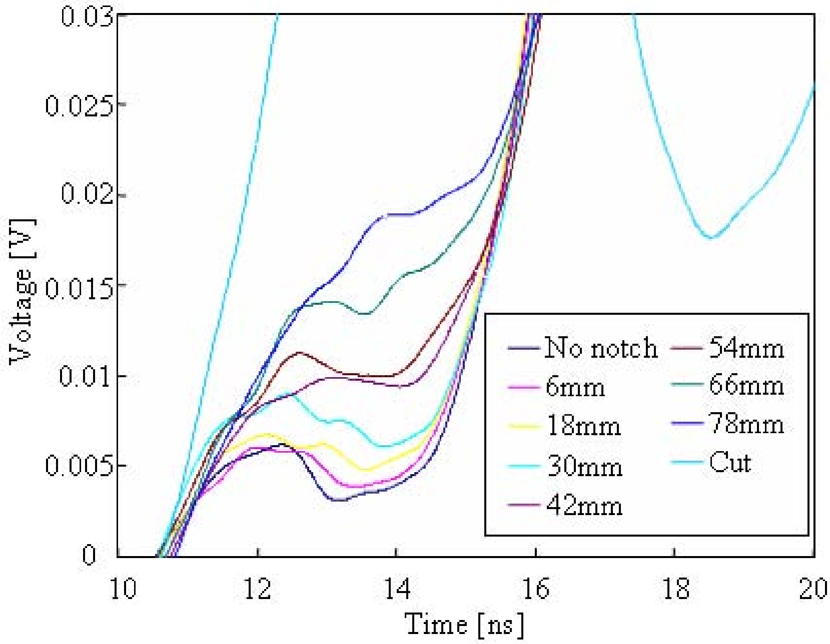


Fig.11 Magnified view of reflected wave

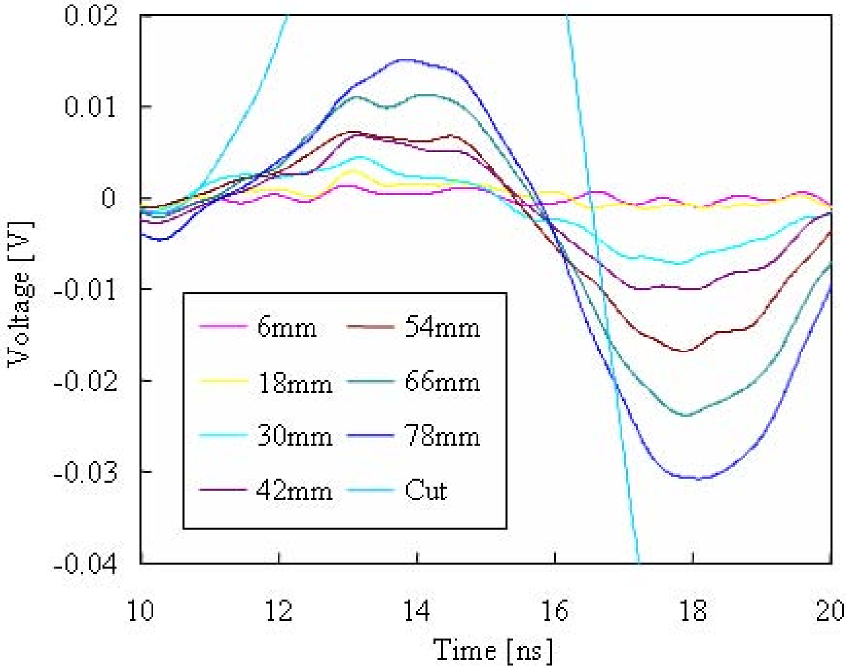


Fig.12 Difference from the reflected wave from the end

Figure 12 shows the results of the reflected wave difference from the reflected wave from the end of the specimen. Even from this figure, it is quite difficult to distinguish small length notch wave. To improve this, information technology is required. In the present study, a cross-correlation analysis is applied to distinguish the results.

Cross-correlation analysis. In the present study, a cross-correlation analysis is adopted to distinguish the reflected wave at the notch from the normal wave without notch. Assume there are two signal sets of ***a***={a_i} and ***b***={b_i} (i=1,2,…,n). The cross-correlation between the two sets of signals is defined as

$$r = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2}\sqrt{\sum_{i=1}^{n}(b_i - \bar{b})^2}} \tag{2}$$

where $\bar{a}$ and $\bar{b}$ are the arithmetic averages of the two sets of the signals. When the Eq. (1) is applied to this problem, we can obtain the difference of the signal between the original signal without notch and the signal with notch. However, the cross-correlation analysis does not include the location of the difference. Therefore, we have to cut the entire signal into small size segments to distinguish the time when the difference occurs (narrow band cross-correlation analysis) . In the present study, various kinds of time interval from 0.5 to 10 [ns] are used to find appropriate time interval for the cross-correlation analysis. High cross-correlation value of Eq. (1) means the two sets of signals have highly correlated, or, in other words, similar. The highest value is 1. This means the two signals are completely identical. The value of -1 means the signals are identical except for sign. Time step wise enables us to identify the time when the difference occurs. Figure 13 shows the results of the cross-correlation analysis. Red color means the value is smaller than 1. The abscissa is the time (time is defined as the averaged time of the time interval segment) and the ordinate is the measured values of the cross-correlation values.

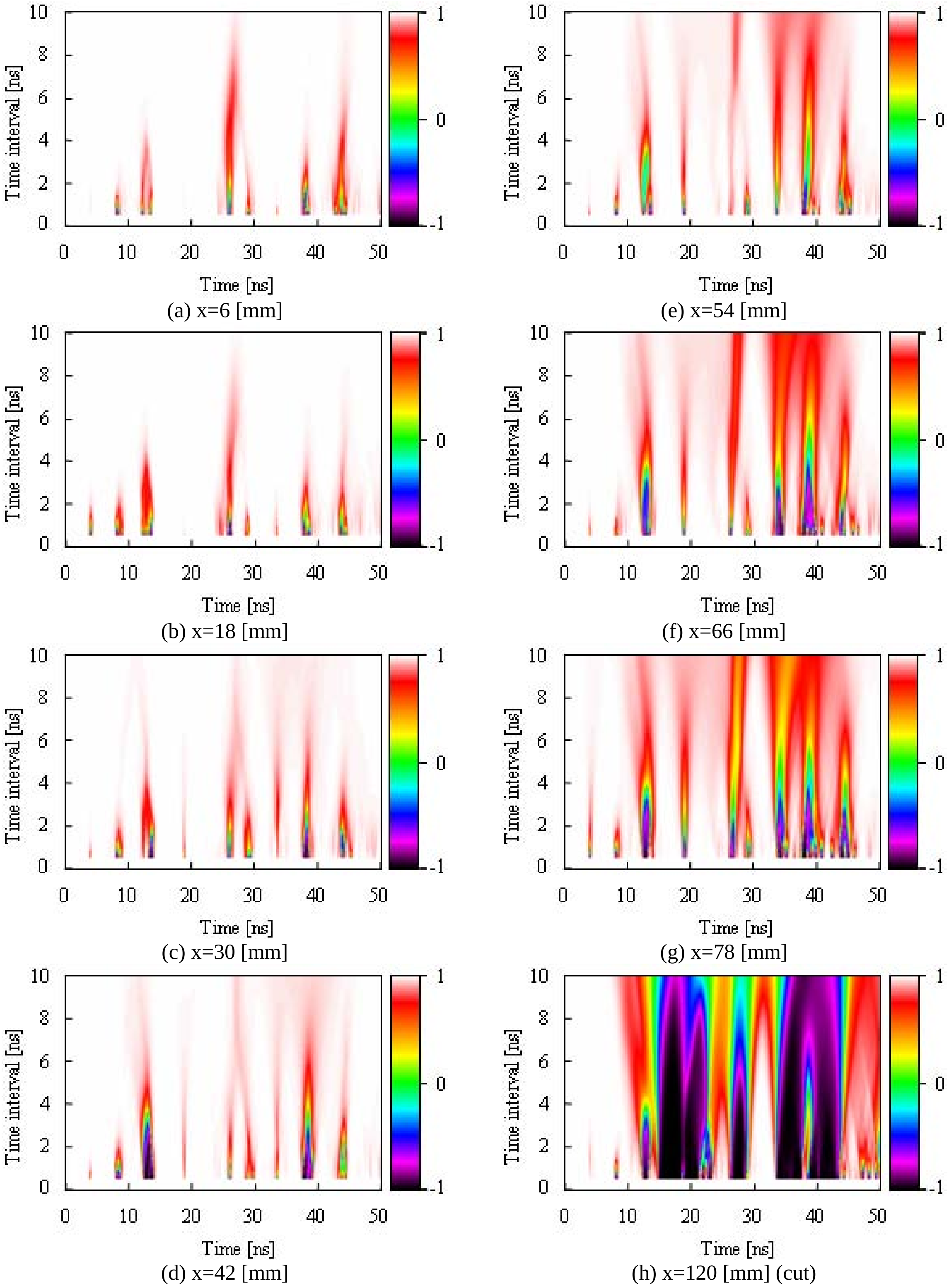


Fig.13 Correlation coefficient of TDR waveforms of no notch and x [mm] notch by a pulse waveform.

From Fig.13, even for the results of 6 mm, we can detect the notch at 12 [ns] for 3 [ns] intervals. When the interval is longer, the difference is lost in the other signals. When the interval is shorter than 3 [ns] other differences caused by noise can be observed. Using the threshold value of 3 [ns], we can detect the notch of 6 [mm] using the cross-correlation analysis.

Conclusions

The present study shows the availability of Time Domain Reflectometry (TDR) for damage detection of CFRP. The TDR may enable us to use the electrical resistance change method with only a few electrodes for large body of aerospace structures. Since the present study is a first step of the new application of the TDR, basic researches are performed here. Modifications of reflected signals are performed to obtain high reflected waves, and notch detections are conducted using 2 [m] long CFRP unidirectional plate. The results obtained are follows.

(1) Impedance matching and noise reduction using an aluminum plate enables us to obtain high reflected pulse waves.
(2) Longer than 30 [mm] notch can be detected using the TDR without using other information technology.
(3) Using the narrow band cross-correlation analysis, a small notch of 6 [mm] length can be detected using the TDR.

Future works

The present study deals with the kick-off of the application of TDR. The CFRP plate is used as a flat cable here. We have to investigate the effect of small width of the used electrode to distinguish the damage location in the width direction. Effects of stacking sequences are also important issue of the present method. Impedance matching between the normal cable and the CFRP plate is also important problem to apply the method to the actual CFRP without using the aluminum plate. Other types of damages such as delamination or impact damages must be investigated using the TDR.

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